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ADP011188

TITLE: Antenna-Coupled Infrared Sensors: Next-Generation Uncooled IR Focal Planes

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This paper is part of the following report:

TITLE: The Annual AIAA/BMDO Technology Conference [10th] Held in Williamsburg, Virginia on July 23-26, 2001. Volume 1. Unclassified Proceedings

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The following component part numbers comprise the compilation report:

ADP011183 thru ADP011193

ADP204784 thru ADP204818

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## **Antenna-Coupled Infrared Sensors: Next-Generation Uncooled IR Focal Planes**

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*This research sponsored by BMDO through  
contract N66001-98-D-6003-0011 issued by  
SPAWAR Systems Center, San Diego.*

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### **Abstract**

We report on recent advances on a completely new type of uncooled IR sensor technology, which uses ultrasmall metallic antennas to capture the radiation. By electronically changing the 30-THz current-wave distribution on the antenna structure, the polarization and wavelength responses of the IR sensor can be changed dynamically in response to a small (100 mV) control voltage. The operational advantages to seeker systems are that enhanced target discrimination is possible by means of the polarization and wavelength signatures. Furthermore, the implementation of an imaging spectrometer or polarimeter can be done directly on the IR focal plane array, without the need for external optical filter elements. This reduces the weight and power requirements of the imager system, eliminates mechanical switching mechanisms, and avoids pixel-registration-error artifacts.

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We are developing antenna-coupled uncooled IR sensors, suitable for integration into focal-plane array formats, which are specifically optimized for BMDO-type applications.

### Presentation Outline

- Why IR Antennas?
- Advantages for BMDO Applications
  - Polarization and Wavelength Tuning
  - Small Pixel Size
  - Retrofit to Existing FPA Architecture
  - Fast Response Time
  - Passive Cold Shield
- Future Work

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Extension of antenna-coupling techniques to the thermal infrared portion of the spectrum allows IR sensors to be developed that have distinct advantages for BMDO-type applications involving high-resolution target tracking and target/background discrimination. These new IR sensors operate uncooled, and have increased capability in a smaller, lighter package because mechanical assemblies for motorized filter wheels are eliminated.

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## Why IR Antennas?

Planar lithographic antennas are common in the microwave and millimeter-wave portions of the spectrum.

At any wavelength, an antenna allows a sub-wavelength-sized sensor to present an appreciable capture cross section to EM radiation.

*What is the advantage of antennas in the 8- to 12-micron IR band?*

Antenna coupling allows separation of the radiation-collection and radiation-sensing functions.

*The collection and sensing functions can be optimized separately.*

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The IR antennas are analogs to planar lithographic antennas that are common at longer wavelengths. They are fabricated on a silicon substrate that is transparent to the radiation of interest. The monolithic configuration leads to a compact, robust packaging that will withstand vibration and high g-forces.

The length of the antenna structure is on the order of one dielectric wavelength in the resonant dimension (along the antenna arm). In the cross-arm direction, the width of the structure is typically on the order of 0.1 of the dielectric wavelength to ensure mode purity. For systems operating in the 8-12  $\mu\text{m}$  band, and considering that the refractive index of silicon is around 3.5, we find that the on-chip resolution requirement is around 0.2  $\mu\text{m}$  (200 nm). Structures with this resolution are conveniently fabricated with direct-write electron-beam techniques, which have a typical resolution of less than 100 nm.

Incoming electromagnetic radiation induces current waves to flow in the metallic arms of the antenna. These current waves oscillate at approximately 30 THz, and are detected, typically by a square-law detector such as a bolometer located at the feed region of the antenna. The electric fields across the terminals of the sensor are enhanced by the concentration function of the antenna, compared to the incident fields that illuminate the sensor.

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## Advantages for BMDO Applications

What aspects of antenna-coupled IR sensors are particularly well suited for BMDO applications, as compared to other uncooled IR sensor designs under development for terrestrial applications?

- Polarization tuning - on chip
- Wavelength tuning - on chip
- Small pixel size
- Retrofit to existing FPA architecture
- Fast response
- Passive "cold shield"

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Having "smart sensor" functions integrated on-chip will enhance sensor-platform capabilities for discrimination of targets from backgrounds and decoys. Polarimetric and spectral data have been shown to be valuable for this purpose, and the ability to implement these functions without any moving parts or mechanical assemblies will result in reduced weight, lower cost, and higher survivability for the sensor packages.

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## **Polarization and Wavelength Tuning**

Antenna-coupled IR sensors allow real-time on-chip tuning of polarization and wavelength response

Pixel-integrated imaging polarimeters and spectral imagers directly on the IR focal plane array, without the need for external optical filter elements.

Reduce weight, eliminate mechanical switching mechanisms, and avoid pixel-registration-error artifacts.

Enhance passive-sensor capabilities for real-time target feature extraction, countermeasure discrimination, and clutter removal.

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In most imaging spectrometers and imaging polarimeters there is a time lag between usable frames of information because of the need to move the filter-wheel assemblies. For dynamic scenes, this registration error causes artifacts in the processed image, reducing sensor accuracy. With on-chip tuning of polarization and wavelength, data will be able to be collected at the full frame rate of the sensor, resulting in better frame-to-frame registration of the data sets.

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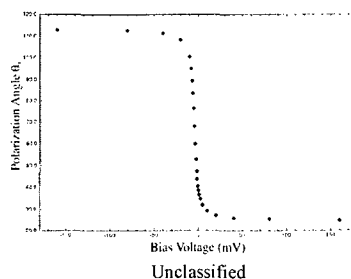


## Polarization Tuning

Many targets of interest have polarization signature that can be exploited to assist in detection and discrimination tasks.

On-chip polarization tuning demonstrated using IR spiral antenna - a US patent (6,037,590) has been awarded to UCF for this work.

Horizontal-to-vertical polarization tuning with  $\pm 0.1$  V control voltage.



The above curve is measured data, taken at 10-micron wavelength.

The uncooled IR sensor that was used for these experiments was a rectifying diode, of metal-metaloxide-metal (MOM) construction. Continuous variation of the bias voltage applied to the diode resulted in a rotation of the principal axis of the polarization ellipse of the spiral antenna. This effect is caused by a variation in the capacitance of the detector with applied bias voltage.

The sensor was coupled to a IR spiral antenna. The antenna arms cross at 90 degrees at the diode location, and it is this asymmetry that is exploited to accomplish the polarization tuning.

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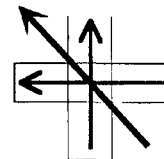
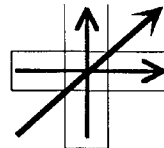


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## Polarization Tuning

Mechanism is capacitance change of sensor at focus of antenna -- changes THz-frequency standing-wave current pattern on the antenna arms.



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There are two fundamental current-wave modes that propagate on the arms of the antenna, a balanced and an unbalanced mode, with amplitudes  $B$  and  $U$  respectively. The  $B$  mode has a  $\pi$  phase shift between the current wave on both arms (at the location of the diode), and the  $U$  mode has both current waves in phase (at the diode). The  $B$  and  $U$  modes have a different polarization signature. The mixing ratio  $U/B$  is a function of the capacitance of the sensor load impedance, and determines the aggregate polarization state as a linear superposition. The fact that the sensor capacitance is a function of the bias voltage is the tuning mechanism.

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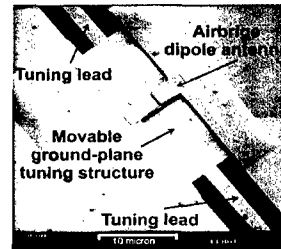
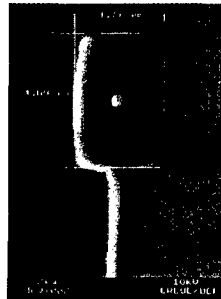


## Wavelength Tuning

Spectral information is an important discriminator characteristic. We are pursuing two approaches for wavelength tuning of IR antennas.

Patch antennas: narrow resonance - capacitively tune electrical length.

Dipole with tuned cavity: movable-ground-plane structure - variable distance between ground plane and antenna.



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Most antenna applications require broadband response. We are developing antennas with a tunable narrowband response. We begin with two design forms that stand to satisfy our requirements: a patch antenna and a tuned cavity antenna. Both show narrow resonance behavior compared to other lithographic antenna designs.

For the patch antennas we tune the electrical length of the patch by means of a variable capacitor structure imbedded under the patch.

For the tuned-cavity antennas, we vary the height of the ground plane electrostatically and move the primary resonance of the dipole that is suspended above the cavity.

In both cases, the design bias voltage is on the order of 100 mV for tuning.

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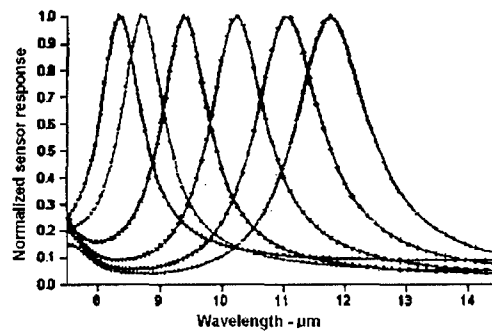


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## Wavelength Tuning

Design goal is to split up 8-12 micron band into several sub-bands.



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The above curves are simulations of sensor spectral response obtained from our electromagnetic codes for the patch-antenna design.

Our design goal is to split up the 8 to 12 micron band into 4 to 6 subbands, of FWHM of 0.5 to 1 micron.

This set of spectral passbands that will assist in LWIR target discrimination. If very narrow responses can be achieved, there is a possibility of hyperspectral imaging, for higher photon-flux levels.

We are also investigating switchable 3-to-5 and 8-to-12 micron band (MWIR/LWIR) sensors.

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## Small Pixel Size

Present uncooled IR FPAs: pixel-to-pixel spacing of around 25 micron.

Higher pixel densities are desired for high-resolution sensing and target-tracking applications.

Smaller pixels allow higher resolution for given size chip, and potential to oversample the image.

But classical IR sensors are at least a few wavelengths in  $x$  &  $y$  dimensions - this limits FPA pixel density that can be achieved with the usual designs.

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Classical IR sensors must be a few wavelengths in dimension in order to present a reasonable capture cross section to the incoming electromagnetic radiation. In contrast, the collection area for an antenna-coupled sensor is defined by the antenna structure and can be substantially more compact - on the order of one wavelength on a side.

This will allow construction of IR FPAs whose pixel densities are limited more by the underlying multiplex electronics than the sensor areas themselves. This is an interesting option particularly for high-resolution tracking systems, for which oversampling of the optics impulse response provides extra accuracy for point-source location algorithms.

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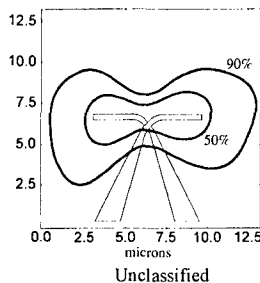
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## Small Pixel Size

Antenna-coupled sensors have a collection area as small as wavelength squared - nearly a point receiver.

Diagram below shows measured encircled-energy contours for an IR antenna illuminated at 10 micron. About a 10-micron by 5-micron collection area for this sensor.



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The encircled energy contours above were measured using a scanned-spot method, where the illuminating beam (about 25 micron diameter) is deconvolved from the measured near-field response of the antenna. The input beam must be especially well characterized by knife-edge data in order for the convolution to converge because of the large beam size compared to the antenna response.

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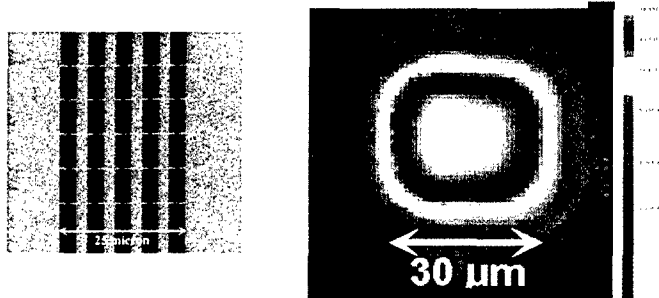
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### Small Pixel Size

Other applications do not require such high pixel densities.

In those cases, antenna-coupled IR sensors are interconnected to form pixels with uniform response across areas as large as 50 micron by 50 micron, which can be retrofitted to existing FPA multiplexers.



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The antenna array shown is a series-parallel connection, which is one configuration we have investigated for making area-receiver arrays. All of the sensor outputs combine to give a single, phased-array response. The measured spatial responsivity was obtained for 10 micron illumination, and is uniform across the array. This kind of an antenna array constitutes a single pixel of a FPA, and either a 25-micron or 50-micron pixel design can be constructed.

We are investigating the possibility of varying the inter-element phase between these antennas and thus obtaining electronic steering of the sensor FOV.

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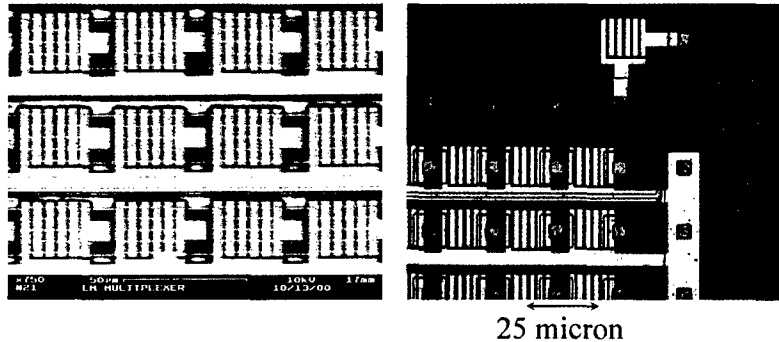


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## Retrofit to Existing FPA Architecture

We have demonstrated fabrication of antenna-coupled IR sensor pixels directly on standard commercial FPA multiplexer circuitry of 25-micron pitch. We are teaming with Lockheed-Martin and other commercial firms in this development effort.



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We have fabricated some of these antenna arrays as individual pixels on a commercial Lockheed-Martin multiplexer, to verify that we can perform the lithographic steps required and maintain operability of the underlying multiplexer. These tests were successful, and we are proceeding to develop antenna-coupled pixels that are optimized for coupling to the multiplexer as far as impedance is concerned. We have also subcontracted to ADIC, Inc. in Orlando for design assistance specifically for multiplexer-optimization issues for uncooled antenna-coupled sensors.

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## Fast Response Time

Some target-tracking scenarios demand fast response times that can not be met by existing uncooled IR FPAs, which run at 30 frames/sec.

The antenna-coupling technique greatly reduces the thermal mass of the sensor material for a given collection area - this allows very rapid responses, on the range of 100 nanosec if desired.

There is the usual thermal-detector tradeoff of response speed for SNR, and this trade is under the designer's control, depending on the thermal coupling between the sensor and the substrate.

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One additional benefit of antenna-coupled uncooled IR sensors is that the thermal mass of the sensor has been reduced by more than an order of magnitude, allowing for very fast response time. This has direct application to the construction of uncooled IR FPAs that can run at elevated frame rates, which at present can only be implemented in cooled photon sensors because of the inherently slow response of the present uncooled IR sensors.

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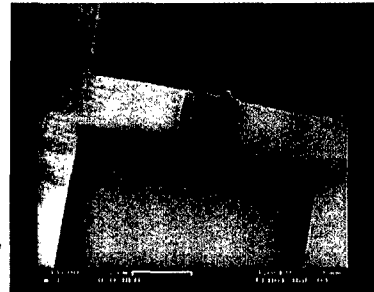
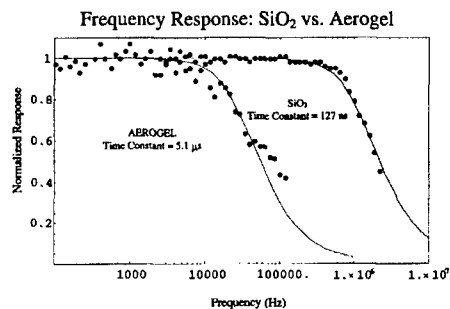


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## Fast Response Time

Depending on thermal isolation of the sensor, the time constant can be controlled by design. Aerogel isolation layer and air-bridge architecture produce slower response times consistent with usual FPA frame rates, while more thermal coupling produces faster response.



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We are investigating a variety of thermal-isolation techniques that give good sensor responsivity while maintaining fast response speed.

Aerogel-coated substrates have been obtained courtesy of Sandia National Labs, which provide excellent thermal isolation. Other options we have fabricated are air-bridge structures which have approximately the same time constant.

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## Passive Cold Shield

Present devices are limited by same noise mechanisms as the current generation of uncooled IR sensors:  $1/f$  noise and Johnson noise.

Fundamental limitation of SNR is thermal-fluctuation noise - analog to photon-detector background noise, but for thermal detectors.

The background performance limit has not been reached yet for commercial uncooled systems, but is on horizon - several years out.

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Background thermal-fluctuation limit has not yet been reached for uncooled IR sensors, but as  $1/f$  and Johnson noise contributions are steadily reduced, this limit will ultimately be achieved.

At that point, further reductions in noise will depend on development of background-rejection methods, and antenna-coupled sensors provide a completely passive, uncooled mechanism for accomplishing this.

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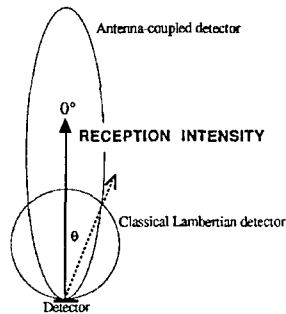


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## Passive Cold Shield

In order to reduce background FOV for a classical IR sensor, an actual cold shield is required - but antenna coupling of the sensor provides a mechanism to implement a passive cold shield by control of the angular antenna pattern.



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The angular response of the antenna pattern will act as a cold shield, rejecting background radiation from outside of a predetermined acceptance angle. This background rejection is inherent to the sensor itself, and is completely passive, requiring no cold surfaces in the optical system.

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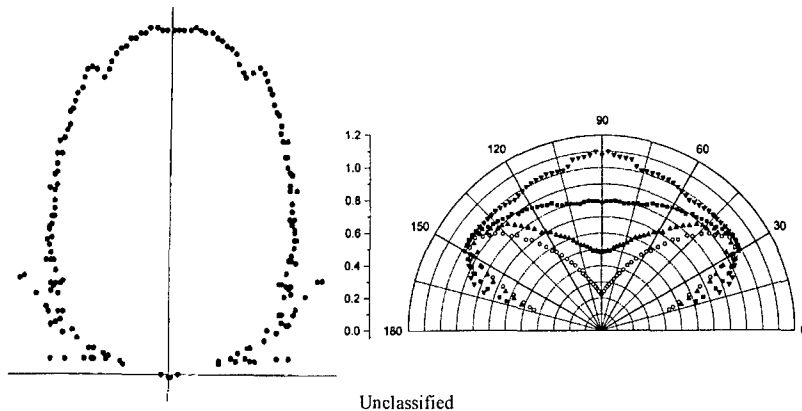


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## Passive Cold Shield

We measure the angular antenna pattern using collimated IR radiation, and have verified forward gain characteristics, as well as dependence of IR antenna pattern on the antenna length.



We have measured IR antenna patterns that indicate a substantial forward-gain characteristic, and also that the antenna pattern changes as expected with the length of the element.

We are also investigating electronic control of the width of the antenna pattern, which may open the way for adaptive cold-shielding with a completely uncooled system.

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## Future Work

Bringing in-house e-beam fabrication capabilities online now. This puts all design, fab., & test facilities for IR antennas under one roof.

Optimizing coupling of sensors to commercial multiplexers

- SNR enhancement
- 32-by-32 FPA near-term goal.

Continuing development of polarization tuner.

Continuing development of wavelength tuner and dual-band designs.



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We are currently commissioning an electron-beam fabrication facility in house at UCF/CREOL, which will allow much reduced turnaround times for development of new designs. This brings all design, fabrication, and test facilities for IR antennas under one roof.

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